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# MECHANICAL PERFORMANCE IN FLEXURE FOR TWO SPANS OF TRUSSES FROM *HIERONYMA ALCHORNEOIDES* AND *GMELINA ARBOREA* WOODS FASTENED WITH NAILS AND SCREWS

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The present study had the objective of determining the behaviour of Pratt-type trusses made from *Gmelina arborea* and *Hieronyma alchorneoides* lumbers relative to loads, displacement and design load stiffness using two types of fasteners (nails and screws) for two spans (6 and 9 m). It was found that the maximum load values were greater in *H. alchorneoides* lumber trusses than *G. arborea*. Design strain values showed that trusses fabricated with *H. alchorneoides* wood had higher design properties than *G. arborea*. The trusses with a 6-m span showed strength and design strain values greater than those with a 9-m span, but lower displacement values. No significant differences appeared in the different types of fastener used. Nonetheless, the load vs. strain behaviour suggested that trusses fabricated with screws presented better properties than those fastened with nails.

Keywords: Framing, wood structures, tropical species, stiffness, truss joint

## INTRODUCTION

In the last ten years, the use of lumber for civil constructions in Costa Rica has decreased (Serrano & Moya 2011). Over 50 percent of the total volume of lumber was consumed by the construction sector in previous decades, however, recent numbers indicate a reduction to just 24 percent. It is reported that only 10 percent of structures are currently being made of wood (ONF 2015). In the past, wooden constructions in Costa Rica were largely of the framing type, built from 5.0 × 7.5 cm transversal sections and used in structural supports for flooring and walls, as well as for truss-making (Tuk 2010, Moya & Tenorio 2017). Nonetheless, currently, this type of wooden structure has been substituted by other types of materials, such as plastic, steel and concrete (Tuk 2010, Fournier 2008).

Wood trusses are one of the most broadly employed framing structures globally, dating back to the 6th century CE (Barbari et al. 2014). Trusses can maximise structural efficiency because they allow high stiffness in flexure and high load capacity, as a consequence of the structure being divided in a determinate number of pieces. Their dimensions and joint methods provide lower stress levels in comparison to other kind of structures, such as beams (Woods et al. 2016).

In wood trusses, the critical node of this system transmits the thrust acting in the top chord to the tie-beam by means of a post (Barbari et al. 2014). A series of structural aspects can be observed in operation of the forces present in the truss, such as displacement behaviour in relation to loads applied, strength, design strains, as well as load and stiffness values (Gebremedhin et al. 1992).

For more than 40 years, metal plates have been widely used for joints in truss assembly, characterised as semi-rigid joints (Gupta & Gebrehedin 1990). These joints allow for some motion (axial, translational and rotational) of the various components in the trusses. However, the strain of the joints can be responsible for a substantial proportion of the total deformation in trusses and often has a significant impact on the distribution of internal loads in truss components (Gupta & Gebrehedin 1990).

 

Presently, there exists much information on the use of metal plates as joints in trusses where their structural characteristics and mode of failure have been determined (Gupta 2005, Bayan et al. 2011, Bouldin et al. 2014). However, this sort of information is scarce for nail and screw joints. Moreover, joints with these types of fasteners have been widely implemented in civil constructions in developing countries, as is the case in Costa Rica, mainly due to their low cost relative to metal plates. Additionally, the available information on the strength attributes of trusses built with fasteners is limited for lumber from tropical species (Sawata et al. 2013).

There have been changes in the species used in frame-type construction processes in many countries, and Costa Rica is not an exception (Serrano and Moya 2011, Wolfsmayr & Rauch 2014). In this country, species used previously from natural forests had densities over 0.6 g $cm^{-3}$, but recently, the use of lumber from forest plantations has grown in popularity, notably *Gmelina arborea* and *Hieronyma alchorneoides* which possess densities less than 0.6 g $cm^{-3}$. The *G. arborea* has been extensively studied, and a series of qualities for structural purposes are attributed to it. Meanwhile, *H. alchorneoides* has been used for commercial reforestation in Costa Rica, and the study of its lumber from forest plantations has revealed high values of structural strength (Moya 2004, Moya et al. 2009, Malavassi 2010, Serrano & Moya 2011, Tenorio et al. 2012, Moya et al. 2013, Tenorio et al. 2016, Moya & Tenorio 2017.

Apart from the scarcity of information on the use of plantation timbers, especially *G. arborea* and *H. alchorneoides*, there is lack of knowledge about their structural properties for truss fabrication. In the case of *G. arborea* wood from plantation trees, it has been shown that it can be satisfactorily employed in the fabrication of I-joists or as web part in I-joists (Moya et al. 2013, Paniagua & Moya 2014, Tenorio et al. 2014). Meanwhile, known uses for *H. alchorneoides* wood extracted from plantation trees are still limited, with the exception of the recent study carried out by Leiva-Leiva et al. (2017), where uses of these two plantation-grown species were presented for the elaboration of wall frames.

In view of this situation, the present study had the objective of determining the behaviour relative to the flexural loads applied, displacement and design load stiffness of 6 and 9-m span Pratt-type trusses, built with lumber derived from plantation-grown *G. arborea* and *H. alchorneoides*, using nails and screws.

## METHODOLOGY

### Lumber used

The lumber used came from approximately 15-year-old *H. alchorneoides* and *G. arborea* trees. Wood from *G. arborea* was obtained from the sawmill, Maderas S & Q 2005, Pérez Zeledón, San José, Costa Rica, while the wood of *H. alchorneoides* was provided by the company ECOCAJAS S.A., Guápiles, Limón, Costa Rica. In green condition, the lumber was 7.5 cm wide and 2.5 cm thick. The lumber was dried in an experimental oven following the drying schedule detailed in Muñoz and Moya (2008) for *G. arborea*, and the schedule detailed by Tenorio et al. (2016) for *H. alchorneoides*. A target moisture content of 14% was established for both species.

### Design and fabrication of the trusses

Pratt-type trusses were constructed, consisting of a bottom chord, two top chords joined at the centre of the length of the truss, vertical posts working in compression and diagonal pieces working in tension (Figure 1). This kind of truss is traditionally employed in Costa Rica (Nieto & Solórzano 1993). This variety uses wooden pieces with dimensions that can be met by lumber obtained from forest plantations, commonly produced in Costa Rica. These dimensions are characterised as having low thickness, as well as widths and lengths not greater than 2.5 m (Serrano & Moya 2011). Trusses of *G. arborea* and *H. alchorneoides* were built in dimensions of 7.2 and 10.2 m and spans of 6 and 9-m, respectively (Figure 1a,b). A slope of 20 percent was applied to the design of both truss sizes. The 6-span-trusses had a 87.5 cm height at the centre and a 14.7 cm at the sides, and were built using 6 vertical posts at 120 cm spacing between their centres, with 7 diagonal pieces in between the vertical pieces (Figure 1a). Furthermore, samples of the 9-span-trusses were 114.5 cm high at the centre and 14.7 cm at the sides, with 11 vertical posts at 120 cm spacing between their centres and 8 diagonal pieces in between the vertical pieces (Figure 1b).

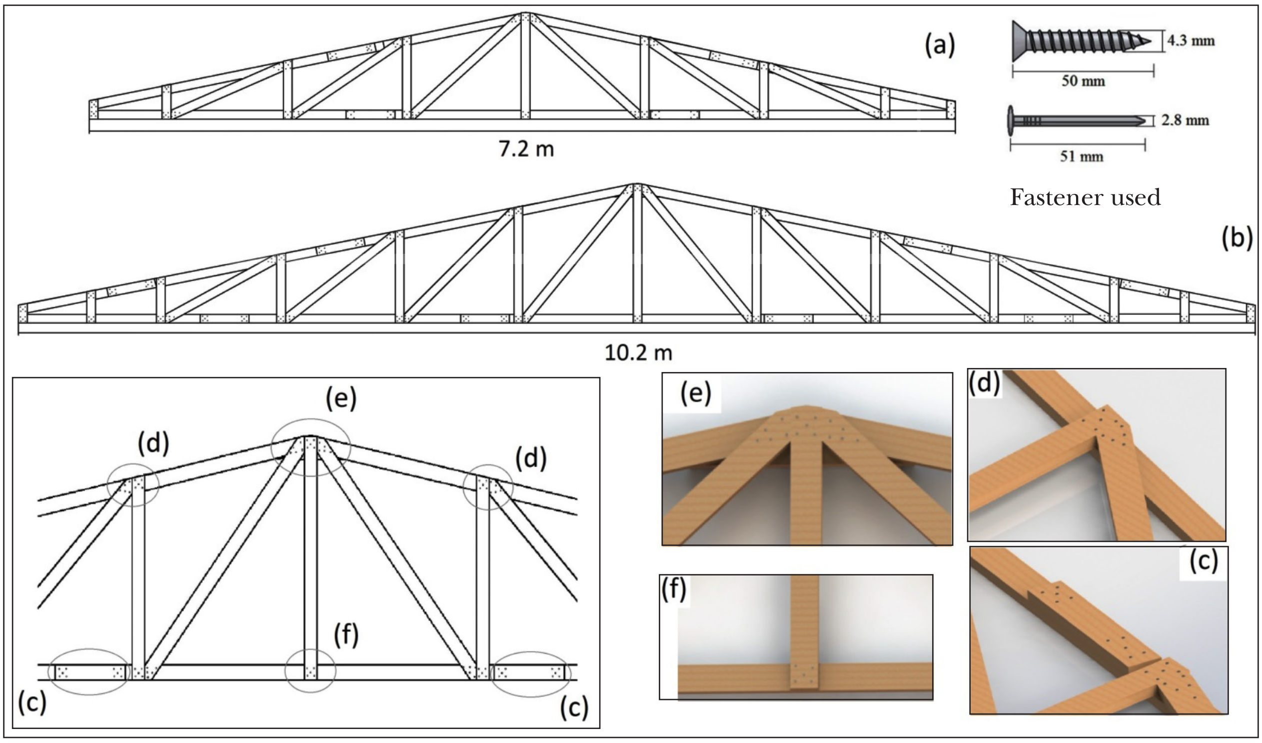


**Figure 1** Model of Pratt truss for 6-span-truss (a), 9-span-truss (b), joint of the pieces at bottom and top chords (c), joint of vertical and diagonal pieces at bottom and top chords (d), joint at top part of truss or peak joint (e) and joint of king post with tie-beam (f)

## Truss construction

For all cases, lumber with dimensions of 7.5 cm wide, 2.5 cm thick and 2.5 m long was used, presenting respective nominal dimensions of 7.1 cm, 2.2 cm and 2.5 m for commercialisation. During truss construction, the centre of the 2.5 m long piece was aligned with the centre of the truss. Then, 2.5 cm thick pieces were placed towards the sides until the ends of the truss were reached. Regarding top chords, a 2.5 m long piece was first placed at the highest point and then 2.5 m long pieces were placed all the way to the ends of the truss. The joint of the pieces at the top chord was placed at half the distance between two vertical posts. In total, four kinds of joints were used in the assembly of the Pratt-type trusses:

*Joint 1: Splice joint*

In these joints, two wooden pieces were matched by placing a 30-cm patch piece at their ends (Figure 1c). This variety was employed in the joints of bottom and top chords.

*Joint 2: Joint between a vertical post and top or bottom chord*

This joint was used where vertical and diagonal (web) pieces met the bottom or top chords (Figure 1d).

*Joint 3: Topmost joint of truss or peak joint.*

This joint was placed at the highest part of the truss and is composed of two top chords, one vertical post and two web pieces. As this is the central part, it was reinforced with a 30-cm long patch piece fastening the vertical and web pieces (Figure 1e).

*Joint 4: Joint of king post with bottom chord.*

This joint was placed at the lower central part of the truss and forms the union between a king post and bottom chord (Figure 1f).

## Types of fastener

Two fasteners were used, i.e. nails and screws. The screws used for the joints were of the flathead type, 50 mm × 4.27 mm, while the nails used were 51 mm × 2.8 mm. Five fasteners were inserted at each end of the wooden pieces. The number of fasteners in each joint was as follows: joint 1 = 10, joint 2 = 10, joint 3 = 24 and joint 4 = 5 (Figure 1c-f).

## Strength tests

Trusses were tested in static flexure. During the test, each truss was mounted on a simple support system, each placed 60 cm inward from the end (Figure 2a, b). To avoid sideways motion, the trusses were kept vertical by means of wooden elements (Figure 2b). Load was applied at three different spots: on the vertical post at the centre of the truss and on the two vertical posts placed at each side of the central post (Figure 2a). For the application of these loads during the test, the construction of a device for the adequate distribution of loads was necessary. This device was made using metal *C* beams with dimensions of 5 cm × 7.5 cm and 6 mm thick, weighing 42 kg (Figure 2a) and was modelled with a finite element using SAP2000 software. It distributes 31 percent of the load to the nodes at the ends of the accessory and 38 percent to the central node. This means, of the 42 kg weight of the device, 17.2 kg were applied on the central node and 12.4 kg were applied on the lateral nodes. For the test, two crackmeter-type sensors were placed in order to measure vertical displacements; one was placed on the king post and the other on the vertical post to the left of the king post (Figure 2a). Two strain gauges were placed to record unitary strain: one for measuring compression in one of the top chords, which was placed on one of the pieces connecting with the top chord, near the centre of the truss, while the other was placed on one of the pieces connecting with the bottom chord subjected to tension, also near the centre of the truss (Figure 2a).

## Parameters determined

Several parameters were assessed: the first group was measured during the test, whereas the rest were determined after the test.

The parameters measured during the test were (i) maximum load capacity of truss, (ii)

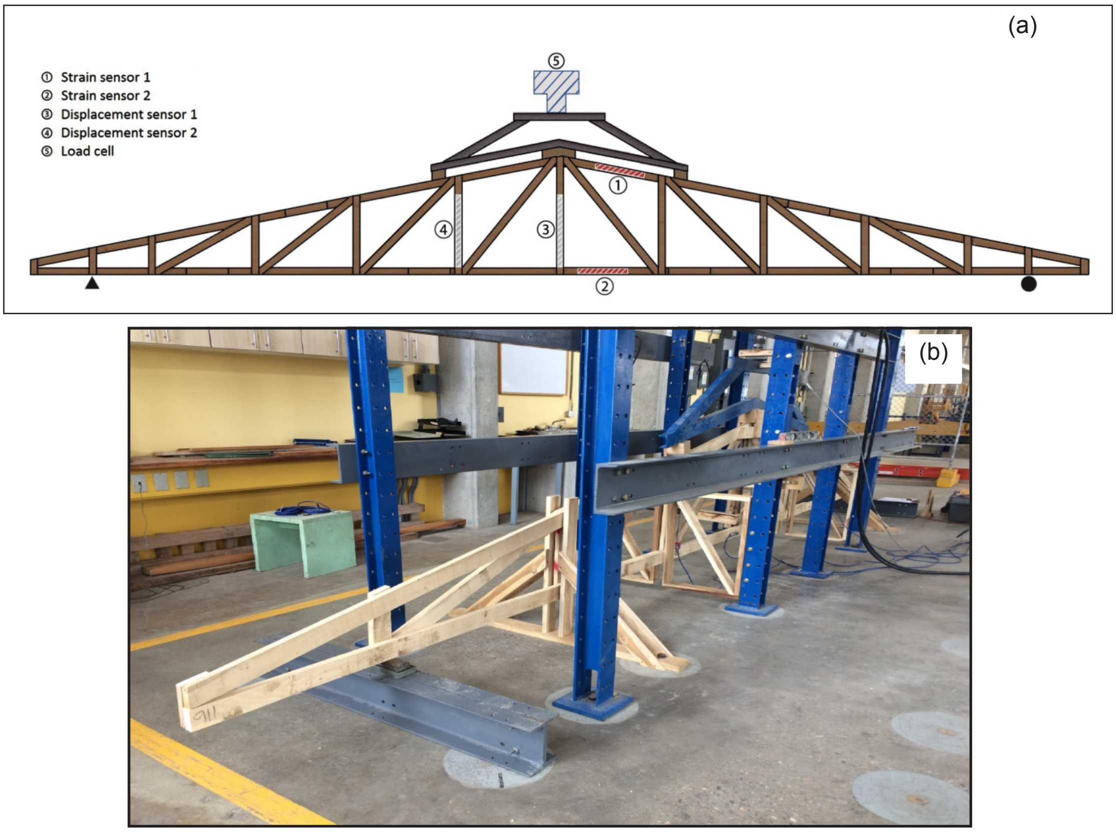


**Figure 2** System for application of loads in truss tests (a) and restrictive elements used to avoid sideways motion of trusses during tests (b)

displacement at centre of truss, (iii) displacement at the side of the centre of truss, (iv) strain in compression at the top chord near the centre of truss and (v) strain in tension at the bottom chord near the centre of truss. Data for displacement (cm), unitary strain (με) and load (kg) were recorded automatically every 5 seconds.

Once the test was carried out, graphs of load vs. displacement and load vs. strain were plotted. Data for load and displacement at the proportionality limit, as well as load and displacement at ⅓ maximum load were then obtained. Likewise, data for load and strain at the proportionality limit of each truss were determined. The weight of the device was added to the values of the load applied to each truss for graphing the curves.

The values obtained were used in determining the design load, which corresponded to ⅓ the maximum load (Formula 1), displacement at given design load (Formula 2), design load stiffness (Formula 3) and stiffness of the truss (Formula 4).

$$\text{Design load} = \frac{\text{Maximum load (kg)}}{3} \quad (1)$$

$$\text{Design displacement} = \frac{\text{Displacement at maximum load (cm)}}{3} \quad (2)$$

$$\text{Design load stiffness} = \frac{\text{Design load (kg)}}{\text{Design displacement (cm)}} \quad (3)$$

$$\text{Truss stiffness} = \frac{\text{Maximum load (kg)}}{\text{(Displacement at maximum load (cm)}} \quad (4)$$

## Experimental design and statistical analysis

An experimental factorial design type $2^2$ was established for the Pratt-type trusses of each species studied, with the two spans (6 and 9 m) and the two fasteners (nails and screws). In total, six *G. arborea* wood trusses were built per span and per fastener type (2 spans × 2 fastener kinds × 6 repeats = 24 trusses), whereas four *H. alchorneoides* wood trusses were built per span and per fastener type (2 spans × 2 fastener kinds × 4 repeats = 16 trusses). The normality of the data was verified for every variable measured (maximum loads and displacements at proportionality limit, strains in tension and compression, design loads, displacement at design load, design load stiffness and truss stiffness). This was followed by an analysis of variance (ANOVA) for each species (*G. arborea* and *H. alchorneoides*) considering 2 factors: span (6 and 9 m) and the fastener treatment used in joints (nails and screws). Finally, for the determination of significant differences between the treatments, a comparison was carried out using the Tukey test.

## RESULTS

### Loads and displacements

The maximum load values obtained in the *H. alchorneoides* trusses surpassed those obtained in *G. arborea* trusses (Figure 3), for the former, these varied from 2.8 to 4.3 kN, and for the latter, from 2.0 to 2.8 kN. In regards to the maximum load in trusses fabricated using *G. arborea* wood, no significant differences were observed between the two fastening methods for both spans, while the 6-span-trusses showed a higher maximum load in comparison to the 9-span-trusses (Figure 3a). Trusses built with *H. alchorneoides* lumber showed the same behaviour as *G. arborea* trusses. No significant differences were observed between fastener types for both spans, yet the 6-span-trusses showed the highest maximum load values (Figure 3b). It must be noted that, although no significant differences were found between the two fasteners used, *G. arborea* trusses fabricated using screws showed the highest load carrying capacity, whereas *H. alchorneoides* trusses fastened using nails presented the highest maximum load values (Figure 3).

Regarding load averages at the proportionality limit, it was found that these loads were greater in *H. alchorneoides* trusses in comparison to *G. arborea* trusses (Figure 4). For the latter, no differences appeared in the loads at the proportionality limit considering either measurement point (central and side), fastening method or span used (Figures 4a,b). Whereas for *H. alchorneoides* trusses, differences were observed in the load averages at the proportionality limit (central and side gauges) in 6-span-trusses, wherein those using nails showed the highest values; for 9-span-trusses, no significant differences were shown between the two fastening methods employed (Figures 4c.d).

In the averages for maximum displacement at the proportionality limit obtained for *G. arborea* and *H. alchorneoides* trusses, no significant differences were observed between either the fastening methods or spans studied (Table 1). Statistical differences were only present in 6-span-

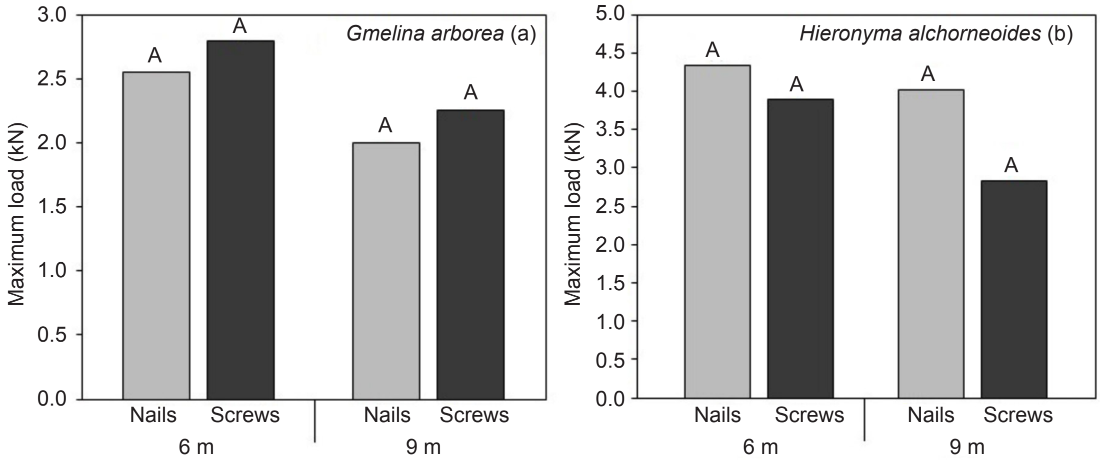


**Figure 3** Maximum load in trusses made of *Gmelina arborea* (a) and *Hieronyma alchorneoides* (b) lumbers, per span and per fastening method

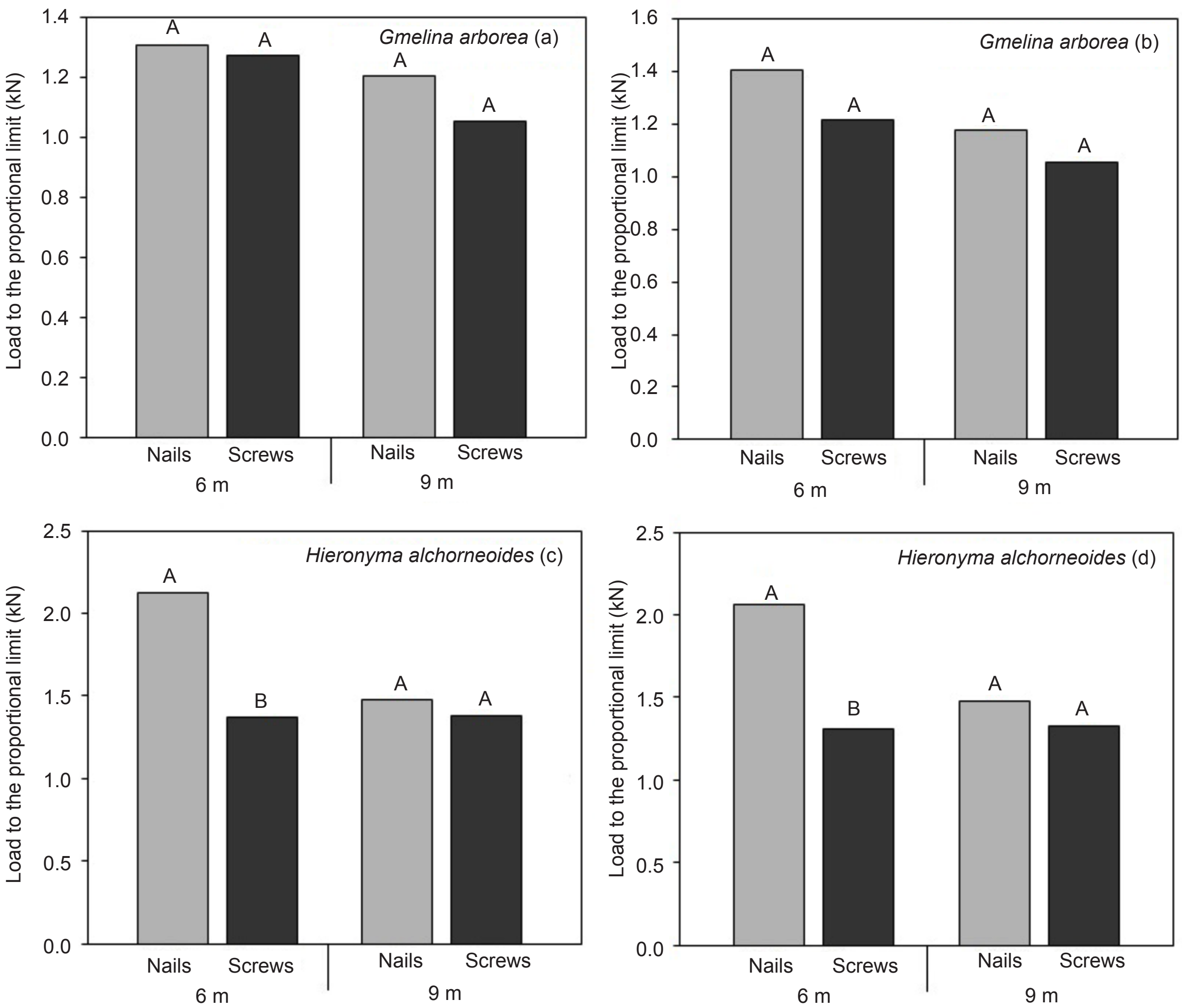


**Figure 4** Load at limit of proportionality at the centre (a) and the side (b) for trusses made of *Gmelina arborea* lumber, load at limit of proportionality at the centre (c) and the side (d) for trusses made of *Hieronyma alchorneoides* lumber, sorted per span and per fastening method used

trusses of *H. alchorneoides* wood, where trusses using nails showed the highest displacement at the proportionality limit at both gauging points (central and side) (Table 1).

The flexural behaviour of trusses is represented by load vs. displacement curves in Figure 5. Trusses of *H. alchorneoides* showed higher load and displacement values than those of *G. arborea* trusses at both points for gauging displacement. Specifically, for *G. arborea* trusses, the two aspects to highlight are: (i) those joined with nails showed greater displacement for a given load and (ii) 6-span-trusses presented higher loads at a given displacement at both measurement points (Figures 5a,b). Regarding *H. alchorneoides* trusses, it was found that those using nails in the 6-span-trusses showed similar load and displacement values to those using screws at both measurement points, however, there was a failure of the screws at lower displacements than those in trusses using nails (Figures 5c,d). In 9-span-trusses of the same lumber, those using nails showed tendency to greater load for a given displacement at both measurement points, compared to those using screws . Trusses using screws also failed at lower displacements, compared to nail-bearing trusses (Figures 5c,d).

## Strains

For both *G. arborea* and *H. alchorneoides* trusses, strain averages obtained for elements under tension, as well as those under compression, showed no significant differences in either fastening means or spans used (Table 2). However, *H. alchorneoides* trusses showed higher strain averages in comparison to *G. arborea* trusses.

Figure 6 shows an example of load vs. strain curves obtained for trusses made of each species studied. The *H. alchorneoides* trusses showed higher strain values, where values of strain in tension were over 700 με at loads of more than 3.5 kN for 9-span-trusses using nails (Figure 6b). In the case of *G. arborea* trusses, the highest strain value was close to 100 με at loads of 1.3 kN for 9-span-trusses using nails (Figure 6a). For both species, 6-span-trusses using nails showed the lowest strains for a given load (Figure 6).

## Design load stiffness

Design load stiffness averages calculated for trusses of the two species is shown in Table 3. No significant differences appeared among the averages obtained for any of the assessed parameters. However, design loads and design load stiffness (central and side) were greater in trusses fabricated with *H. alchorneoides*. In regards to displacements at given design loads, those in *H. alchorneoides* trusses with 9-m spans using nails presented the highest values (Table 3).

For both species, 6-span-trusses showed higher average stiffness values relative to 9-span-trusses, and *H. alchorneoides* trusses showed higher truss stiffness values in general (Figure 7). No significant differences appeared between both fastening used for either span or species.

**Table 1** Displacements obtained in trusses made of *Gmelina arborea* and *Hieronyma alchorneoides* lumbers, per span and fastening method

| Species | Span (m) | Fastener | Maximum displacement: centre (cm) | Maximum displacement: side (cm) | Displacement at proportionality limit: centre (cm) | Displacement at proportionality limit: side (cm) |
|---|---|---|---|---|---|---|
| *Gmelina arborea* | 6 | Nail | 3.96 $^{A}$ (28.92) | 3.38 $^{A}$ (32.04) | 0.43 $^{A}$ (53.97) | 0.47 $^{A}$ (50.56) |
| | | Screw | 3.60 $^{A}$ (38.95) | 3.70 $^{A}$ (36.28) | 0.41$^{A}$ (8.04) | 0.39 $^{A}$ (12.96) |
| | 9 | Nail | 5.61 $^{A}$ (42.11) | 5.69 $^{A}$ (37.08) | 0.74 $^{A}$ (29.03) | 0.81 $^{A}$ (22.50) |
| | | Screw | 5.71 $^{A}$ (30.01) | 5.65 $^{A}$ (31.51) | 0.65 $^{A}$ (21.15) | 0.61 $^{A}$ (22.59) |
| *Hieronyma alchorneoides* | 6 | Nail | 4.63 $^{A}$ (26.48) | 4.61 $^{A}$ (27.43) | 0.75 $^{A}$ (34.20) | 0.76 $^{A}$ (37.71) |
| | | Screw | 3.53 $^{A}$ (4.61) | 3.41 $^{A}$ (14.80) | 0.27 $^{B}$ (28.75) | 0.28 $^{B}$ (29.20) |
| | 9 | Nail | 7.72 $^{A}$ (26.06) | 7.73 $^{A}$ (24.77) | 0.67 $^{A}$ (47.98) | 0.67 $^{A}$ (40.02) |
| | | Screw | 5.32 $^{A}$ (50.67) | 5.63 $^{A}$ (53.22) | 0.74 $^{A}$ (46.91) | 0.85 $^{A}$ (50.05) |

Letters adjoined to averages indicate statistical differences at 95% among type of fastener and angle

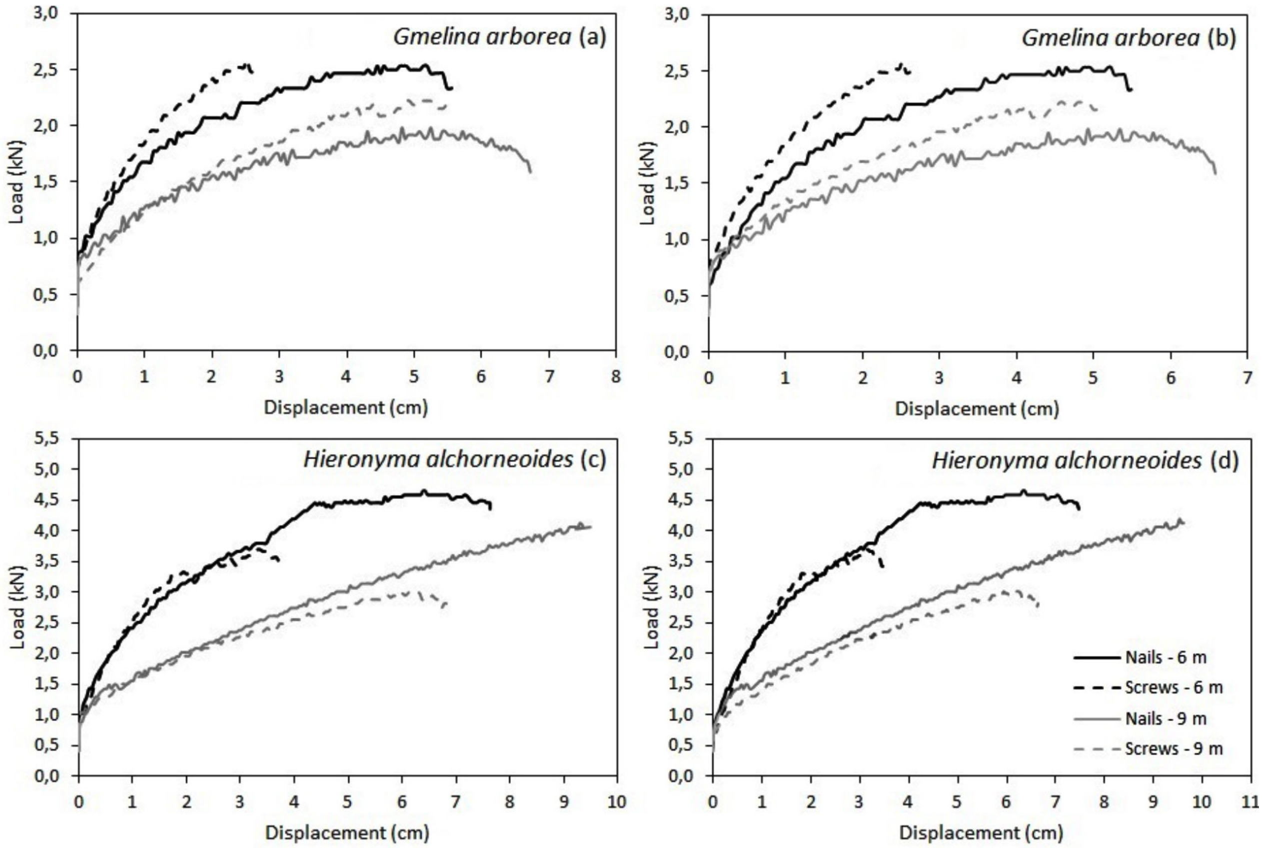


**Figure 5** Load vs. displacement curves for *Gmelina arborea* trusses at central gauge (a) and side gauge (b), for *Hieronyma alchorneoides* trusses at central gauge (c) and side gauge (d), sorted per span and fastening method

**Table 2** Strain values obtained for *Gmelina arborea* and *Hieronyma alchorneoides* trusses, per span and fastening method

| Species | Span (m) | Fastener | Strain in tension (με) | Strain in compression (με) |
|---|---|---|---|---|
| *Gmelina arborea* | 6 | Nail | 34.63 $^{A}$ (40.99) | -28.32 $^{A}$ (-76.77) |
| | | Screw | 28.36 $^{A}$ (32.98) | -16.19 $^{A}$ (-68.03) |
| | 9 | Nail | 21.53 $^{A}$ (59.88) | -33.57 $^{A}$ (-21.89) |
| | | Screw | 14.26 $^{A}$ (75.56) | -33.19 $^{A}$ (-40.06) |
| *Hieronyma alchorneoides* | 6 | Nail | 81.82 $^{A}$ (81.49) | -95.75 $^{A}$ (-88.56) |
| | | Screw | 83.23 $^{A}$ (84.20) | -55.86 $^{A}$ (-48.34) |
| | 9 | Nail | 106.84 $^{A}$ (65.29) | -30.64 $^{A}$ (-91.90) |
| | | Screw | 133.69 $^{A}$ (23.06) | -15.70 $^{A}$ (-89.19) |

Letters adjoined to averages indicate statistical differences at 95% among type of fastener and angle

## DISCUSSION

The highest values obtained in *H. alchorneoides* trusses (for both spans and fastening) for maximum load and displacement averages, as well as those at the proportionality limit (Figures 3 and 4, Table 1), reflect the base specific gravity (SG) of the lumber. Several studies consider that SG is one of the properties best defining mechanical behaviour of wood (Wiemann &

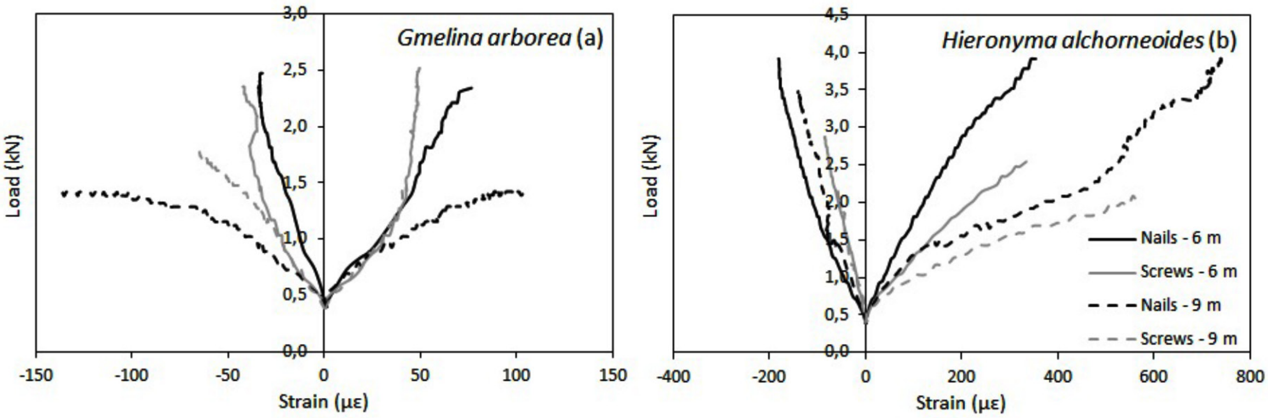


**Figure 6** Load vs. strain curves for *Gmelina arborea* (a) and *Hieronyma alchorneoides* (b) trusses, per span and fastening method

**Table 3** Design strains obtained for *Gmelina arborea* and *Hieronyma alchorneoides* trusses, per span and fastening method

| Species | Span (m) | Fastener | Design load (kN) | Displacement at given design load: centre (cm) | Displacement at given design load: side (cm) | Design load stiffness: centre (kN/cm) | Design load stiffness: side (kN/cm) |
|---|---|---|---|---|---|---|---|
| *Gmelina arborea* | 6 | Nail | 0.85 $^{A}$ (13.57) | 1.32 $^{A}$ (28.92) | 1.13 $^{A}$ (32.04) | 0.69 $^{A}$ (32.42) | 0.83 $^{A}$ (35.08) |
| | | Screw | 0.93 $^{A}$ (21.98) | 1.20 $^{A}$ (38.95) | 1.23 $^{A}$ (36.28) | 0.87 $^{A}$ (37.28) | 0.82 $^{A}$ (29.45) |
| | 9 | Nail | 0.67 $^{A}$ (20.52) | 1.87 $^{A}$ (42.11) | 1.90 $^{A}$ (37.08) | 0.38 $^{A}$ (22.73) | 0.37 $^{A}$ (18.96) |
| | | Screw | 0.75 $^{A}$ (14.87) | 1.90 $^{A}$ (30.01) | 1.88 $^{A}$ (31.51) | 0.41 $^{A}$ (16.43) | 0.42 $^{A}$ (17.50) |
| *Hieronyma alchorneoides* | 6 | Nail | 1.44 $^{A}$ (11.10) | 1.54 $^{A}$ (26.48) | 1.54 $^{A}$ (27.43) | 0.97 $^{A}$ (21.98) | 0.98 $^{A}$ (23.10) |
| | | Screw | 1.30 $^{A}$ (17.92) | 1.18 $^{A}$ (4.61) | 1.14 $^{A}$ (14.80) | 1.10 $^{A}$ (15.30) | 1.14 $^{A}$ (5.18) |
| | 9 | Nail | 1.34 $^{A}$ (20.38) | 2.57 $^{A}$ (26.06) | 2.58 $^{A}$ (24.77) | 0.53 $^{A}$ (16.43) | 0.53 $^{A}$ (14.30) |
| | | Screw | 0.94 $^{A}$ (21.83) | 1.77 $^{A}$ (50.67) | 1.88 $^{A}$ (53.22) | 0.60 $^{A}$ (32.80) | 0.58 $^{A}$ (36.10) |

Letters adjoined to averages indicate statistical differences at 95% among type of fastener and angle

Williamson 1989). Therefore, differences in load and displacement averages at the maximum load, and the proportionality limit between trusses built with *G. arborea* and *H. alchorneoides* are a consequence of the higher SG present in *H. alchorneoides*. The SG reported for *H. alchorneoides* lumber from forest plantations is 0.45, whereas for *G. arborea*, the value ranges from 0.30 to 0.40 (Moya & Tomazello 2007, Tenorio et al. 2016).

The behaviour observed in this study, with the lower strength of *G. arborea* trusses, agrees with the work of Leiva-Leiva et al. (2017) concerning prefabricated timber wall frames of the same two species. Greater strength and lower displacements in structures fabricated with *H. alchorneoides* allows for a better structural performance of the truss.

Trusses with 6-m spans showed higher load and lower displacement values compared to 9-span-trusses (Figures 3 and 4, Table 1) in both species and for both fastening methods. This behaviour is explained by the high-tension forces produced at the lower central part of the structure in 9-span-trusses, which translate into lower strength and greater displacement (McMartin et al. 1984) as opposed to 6-span-trusses, where such forces are smaller. Nonetheless, it is normal for trusses with longer spans to show lower strengths and high strains relative to trusses with lower spans (Caruso et al. 2016).

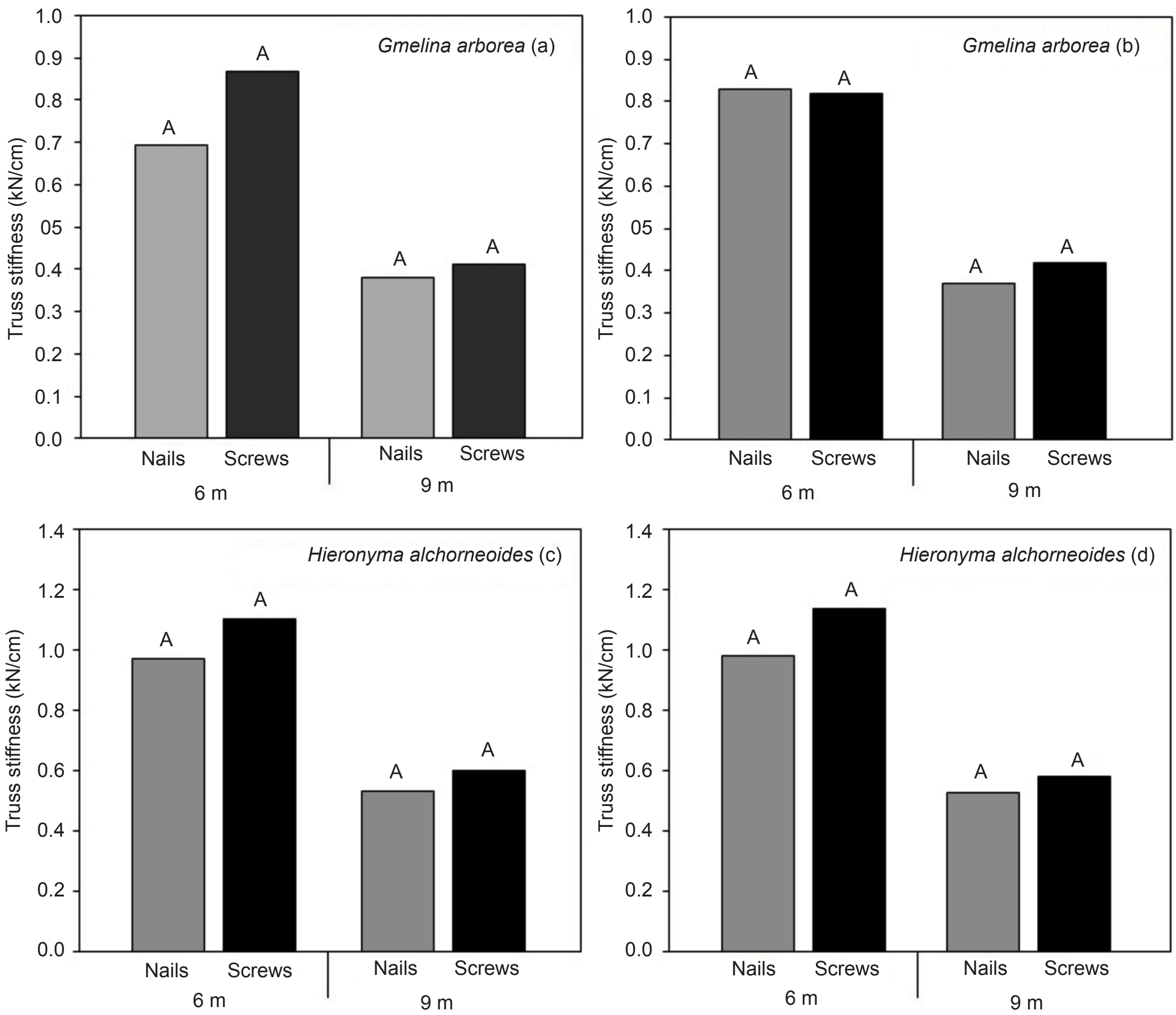


**Figure 7** Truss stiffness for: *Gmelina arborea* trusses, at central gauge (a) and side gauge (b) for *Hieronyma alchorneoides* trusses, at central gauge (c) and side gauge (d), sorted per span and fastening method

Concerning the effect of shear forces on trusses, *H. alchorneoides* trusses using nails showed greater load and displacement values at proportionality limit than those using screws for the 6-span-trusses, but this behaviour was not the same in 9-span-trusses of the same species (Figures 4c,d, Table 1). For *G. arborea* trusses, no differences appeared between the fastening means for both 6-span-trusses and 9-span-trusses (Figures 4a,b). These results indicate that when trusses are built using lumber with high SG (as is *H. alchorneoides*) and short spans are implemented (6 m), where shear force is lower, nails provide more strength relative to screws. In trusses using low-SG wood, there is no difference between using nails or screws, as strength of the truss is likely limited by the fastener choice and not by the span size. The opposite is true for 9-span-trusses, where the loads applied produce great deal of shear forces, and strength is thus limited by the type of lumber, and not the fastener, used in the construction of trusses (McMartin et al. 1984).

An important aspect to clarify in this study is that few significant differences were observed between both fastening means in the load and displacement averages, at both the maximum point and the proportionality limit, with the exception of *H. alchorneoides* trusses with 6-m spans (Figures 3 and 4, Table 1). However, consideration is to be taken with caution, as the lack of differences could be due to the limited number of samples assessed, between 4 and 6 trusses per fastener and span length. A small number of samples limits the degrees of freedom in the ANOVA model and therefore, there is less precision in the evidence of differences between the types of truss evaluated (O'brien 1979).

In the event of having a greater number of samples, significant differences would likely be evident. In fact, in the graphs of load vs. displacement curves for *G. arborea*, it can be seen that trusses using screws showed greater loads than those using nails for a given displacement, in both spans, at the two gauging points (Figures 5a,b). A tendency to present better structural behaviour (high loads and little displacement) is therefore observed in trusses using screws compared to those using nails.

In comparing *H. alchorneoides* trusses with nails to those with screws, the same displacement for a given load was observed until the moment where the screwed trusses failed. After this point, however, nailed trusses presented a slightly higher load and high displacement (Figure 5c,d). This indicates that screwed trusses hold similar loads as do nailed trusses, yet yield lower displacements, which shows that screws produce stiffer joints than nails (Aytekin 2008). Furthermore, the 6-span-trusses were stiffer than the 9-span-trusses in *H. alchorneoides*, as displacements for a given load were lower in the former.

Although no differences appeared statistically between strain averages of *G. arborea* and *H. alchorneoides*, in most cases, nailed trusses showed higher strain values than screwed trusses (Table 2). This tendency reiterates that the components in which strain was measured suffered greater deflection when nailed joints were implemented. The higher strain in trusses with nails was due to trusses showing greater displacement or failing at higher loads, presenting more deformation in the wood.

The different structural behaviour between the 6-span-trusses and 9-span-trusses was made evident by the different strain values of each type of truss. In both species, 6-span-trusses presented greater strain than 9-span-trusses for a given load, especially for elements under tension (Figure 6). This indicates less deflection for 6-span-trusses relative to 9-span-trusses.

Another important aspect to highlight in regards to strain is that, for both spans and fastening methods, elements in tension showed higher deflection values for a given load than those in compression. This situation is to be expected because the element in tension is at the point of maximum deflection, whereas the element in compression is affected by the presence of the king post and thus has more stability (Figure 6).

The results obtained for design load stiffness (Table 3) and truss stiffness (Figure 7) reflect the strength previously explained in the maximum load and displacement values. Trusses made with *H. alchorneoides* showed the highest values as a consequence of the higher SG of the species. Likewise, the 6-span-trusses showed the highest stiffness values due to greater inherent stiffness of the truss size, allowing for maximum performance compared to 9-span-trusses (Figure 7).

## CONCLUSIONS

The strength values obtained for *G. arborea* were lower than those presented in *H. alchorneoides*. These results were reflected in the design strain values derived from the tests, where trusses of *H. alchorneoides* showed higher design values than those obtained for *G. arborea*.

Between the two fasteners utilised in truss fabrication, no significant differences appeared, with the exception of *H. alchorneoides* trusses with a 6-m span. However, load vs. strain behaviour suggests that trusses built with screws presented better properties than nails, as found in *H. alchorneoides* trusses with a 6-m span.

Finally, the length of the span had an effect on truss strength. Trusses fabricated for 6-m span showed greater strength and design load stiffness values than 9-m span trusses, but displacements were lower in 6-m span trusses, a behaviour considered normal as less strain is produced in trusses with shorter spans.

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